CONTAMINATION CONTROL FOR THE EARTH OBSERVING SYSTEM (EOS) MULTI-ANGLE IMAGING SPECTRO-RADIOMETER (MISR)

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BIOGRAPHY

After receiving a B.S. in Physics from U.C.L.A. in 1986, and working 4 years in the field of Microgravity Research, Glenn Aveni became part of the Contamination Control Team at JPL. Since then he has performed molecular contamination analyses of such space flight instruments, besides MISR, as the Wide Field Planetary Camera II (WF/PC II) on the Hubble Space Telescope (HST), the Imaging Science Subsystem (ISS) on Cassini, and the Miniature Integrated Camera and Spectrometer (MICAS) on the New Millennium Program / Deep Space 1 (NMP/DS-1) spacecraft. He is also responsible for the NASA Solar electric propulsion Technology Application Readiness (NSTAR) ion propulsion engine contamination control plan also on NMP/DS-1 and for the Microwave Limb Sounder (MLS) contamination control plan aboard the EOS Chemistry platform.

ABSTRACT

The contamination control activity performed for the Multi-Angle Imaging Spectro-Radiometer (MISR) consisted of an overall system analysis for susceptibility to molecular and particulate contamination from both internal and external sources at the most sensitive sensor wavelength. This analysis considered the system long and short term radiometric stability requirements, the expected sources of contaminants, the transport of those contaminants to the sensors, and the expected effects of those contaminants on sensitive surfaces. The derived requirements, including specific budgets, and a plan to meet them during assembly, test and storage were documented in the EOS MISR Contamination Control Plan. The final phase of control came from monitoring the hardware (recording data and implementing cleaning procedures) during assembly and thermal vacuum testing prior to shipment to the EOS integrator.

KEY WORDS

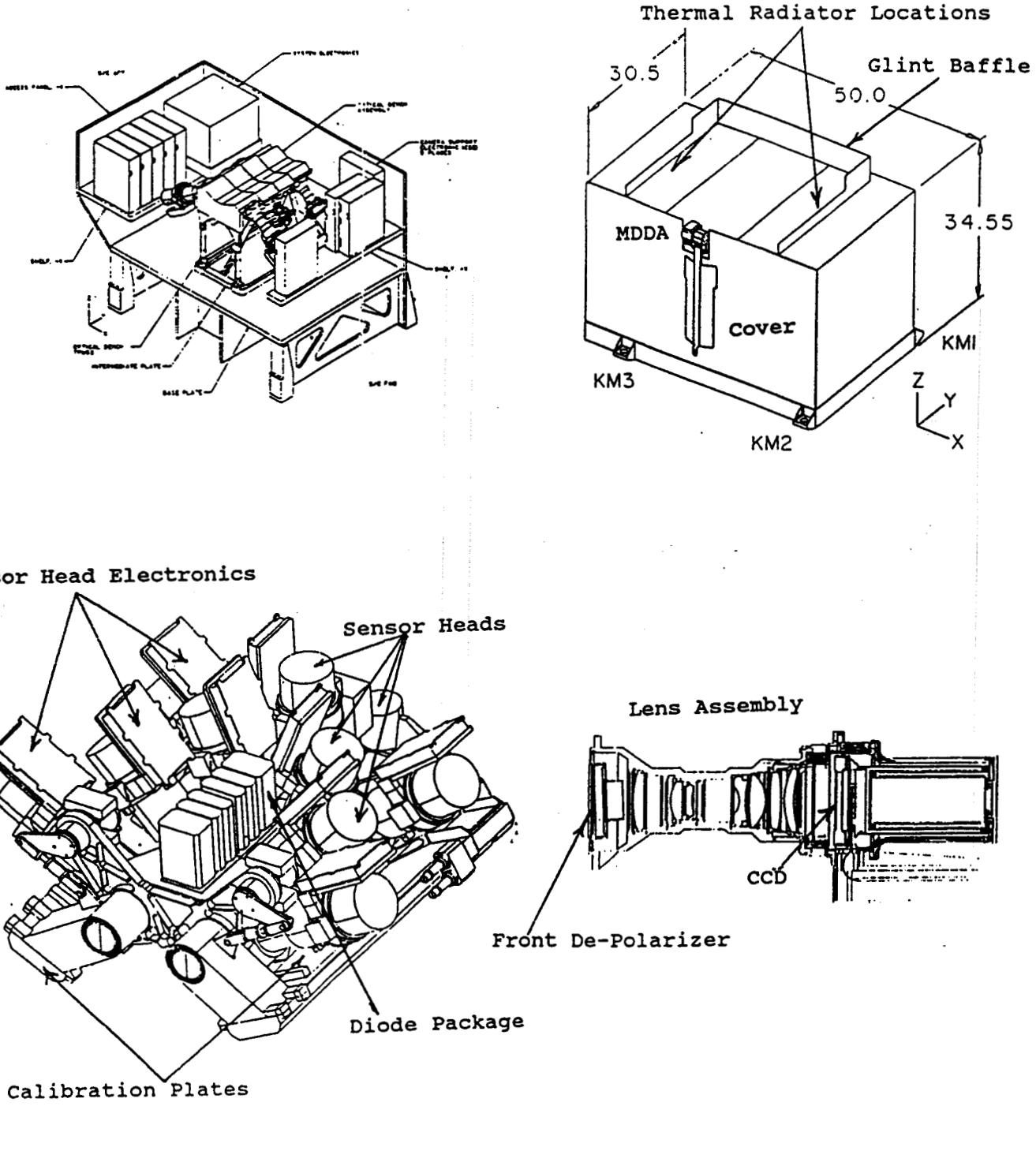
MISR, EOS, Molecular Contamination, Particulate Contamination, Non-Volatile Residue, Signal Throughput Degradation, Transport Factors, Flux, Fluence, TQCM.

CAMERA SYSTEM OVERVIEW

The MISR instrument is a "push-broom" imager that maps the earth with nine cameras at discrete view angles. Four of the cameras are facing forward of the nadir, at 26°, 46°, 60°, and 70°, one is facing nadir, 0°, and four others are pointed in the aftward direction symmetric to the first four. Each camera produces images in four visible and near-infrared spectral bands using charge-coupled device (CCD) line arrays. Via spectral band filters the transmitted wavelengths are centered at 443, 555, 670, and 865 nm. The focal plane structure of each camera houses the detector thermo-electric coolers (TECs) to control the temperature of its detector. The detector package is sealed and can be replaced and interchanged as a unit. Sampling of each line array at discrete intervals creates an image swath along the track of the platform. The size of the swath provides complete global coverage in nine days at the equator and two days in the polar regions. Mission life is to extend over five years.

Absolute radiometric calibration of the MISR instrument in-flight will be performed using special on-board hardware known as the On-Board Calibration (OBC). This includes deployable diffuser plates to reflect sunlight into each of the cameras, a set of nadir looking photodiodes and high quantum-efficient diodes (QEDs) to monitor the plate reflectance, and a

Figure 1
MISR Base Line Configuration



moveable photodiode package to acquire goniometer observations of the plate BRDF.

An actuated optics cover protects the cameras and diodes during instrument assembly, testing, transportation, and system I/T activities. This cover also provides protection of instrument contamination sensitive elements during launch and spacecraft course corrections (Figure 1).

ANALYSIS APPROACH

To quantify the susceptibility of MISR to contamination it is necessary to understand how contaminants effect the overall functional requirements. Based on the radiometry of the system, over the period of a month (short term stability), the radiometric response of the MISR cameras (Reference 1) is not allowed to change by more than 0.5%, and by no more than 2% over the period of a year (long term stability). For a five-year mission life time, this insures that the system light-gathering capability shall degrade by no more than 10%, assuming, in the worst case, that changes in performance are systematic, rather than random. Out of this total 10%, one half or 5% degradation is allotted for contamination effects (Reference 2).

The most sensitive surfaces to molecular and particulate contamination can only tolerate minute amounts of these contaminants. In the MISR assembly these surfaces include the CCD windows, the lens assembly elements, and the de-polarizers (external first elements of lens assemblies), all optical train components, the calibration diodes, the calibration plates and the thermal radiator surfaces (Figure 1). It is over these surfaces that the performance degradation is sub-allocated.

The degradation percentages for molecular contamination are converted into fluences by the following specifications and assumptions. The 400 nm wavelength, λ, (shortest detectable wavelength in the shortest system waveband of 443 nm) has the highest susceptibility to contamination in this system and is therefore chosen to base the contamination requirements on. The molecular contaminant film itself has a complex index of refraction, N, whose imaginary part (the extinction coefficient, k = 0.04) along with the specific wavelength of concern, defines the absorptance, $\alpha = 1.26 \times 10^{4}$ cm^{-1} of that film at that wavelength (Reference 3). Assuming a uniform density, ρ, for the contaminant material of 1 g/cm^3 relates a uniform thickness of contaminant (Reference 4) to a mass fluence, Ψ (ng/cm^2). **I** is the fraction (between 0 and 1) of through-put intensity that relates signal degradation to contaminant amount.

$$\psi = -\frac{\rho}{\alpha}\mathrm{Ln}I \; ; \; \alpha = \frac{4\pi\kappa}{\lambda} \; ; \; N = n + i\kappa \quad \textbf{(1)}$$

A signal degradation of 5% allocated to the optical throughput per camera, corresponds to a mass fluence of 1770 ng/cm^2 of both molecular and particulate contaminants (Table 1) at the system's most sensitive wavelength of 443 nm. This allocation is sub-allocated among the CCD window, 2.7%, the front de-polarizer, 1.7%, and the lens elements, 0.6% (Table 2). The other allowable degradation allocations include 5% for the signal throughput to the calibration diodes, 5% for reflectance degradation of the calibration plates, and a change in absorptance of 0.1 for the thermal radiator surfaces. A "rule of thumb" relates this change in absorptance to 20 μg/cm^2 of contamination.

The allowable amount of particulate contamination comes out of sections 5.6.4. and 5.6.5. of Reference 1 on stray light and contrasting targets, respectively. From experience, the assumptions made for particulates consider the cleanliness of the assembly areas (clean rooms and clean benches) and, as for the molecular case, the element sensitivities. For this analysis the allowable amount of particulate contamination has been allocated by assumed percentages. The obscuration ratios (OR) obtained are the fractional form of these percentages, i.e. an allowable 2% degradation is equivalent to an OR=0.02. Which implies that two percent of a surface, or of surfaces that may degrade, is allowed to be covered by particulates. This OR translates into a particle cleanliness level (PCL) that the hardware surfaces are maintained to during assembly, test, and transportation.

The above sensitive surfaces are effected the most via transport paths to critical contamination source locations. In MISR these locations are the volumes surrounding the CCDs (between the

CCD windows and the last lens elements), the electronics packaging that connects directly behind the CCD heads, the internal volumes of the lens assemblies, the environment outside of the camera housings but inside the MISR assembly, the external environment directly in front of the MISR aperture, and the contamination from the EOS platform and other EOS instruments. The sources themselves include molecular contamination from inside the camera housings, molecular contamination from outside the camera housings but internal to MISR, molecular contamination from outside MISR, and particulate contamination collected during assembly, test, transportation and launch redistribution. Table 3 lists (as an example of the other elements of the system) the sub-allocation of contaminants on the CCD window due to the source of that contaminant.

Critical to determining element sensitivities are specific thermal data, transport geometries, and materials. Sub-system temperatures effect source outgassing rates of materials and re-emission rates of contaminants. The re-emission rate constants are calculated based on collection surface temperatures.

The unitless transport factors, F_{ij}, have been calculated from assumed, flow-restricting vent paths. The calculations are made by simplifying the geometry of the system into circles and squares for area, and cylinders and rectangular parallelepipeds (boxes) for volume. The lengths and sizes of the paths are essentially turned into effective cross-sectional areas, A_{eff}, that contaminants travel through to reach sensitive areas.

$$F_{ij} = \frac{A_{eff}\, A_{CCD}}{(A_x + A_{eff})(A_v + A_{CCD} + A_{eff})} \quad (2)$$

A_{CCD} is the surface area of a CCD window, A_x is the effective cross-sectional area of transport away from the CCD and A_v is the cross-sectional area of venting other than the CCD.

In order to meet the requirements shown in Tables 1, 2 and 3, a process of verification was established. This process involved sub-allocating the allowable fluences (Table 3) that may collect, to the source components producing the molecular contamination. Tables 4 and 5 list the fractional percent of a collector's sub-allocation that a source may contribute to that collector. This allowable amount of source was then translated into a measurable verification requirement (units of Hz/hr)[1]. The relationship between collectable flux and source flux is addressed below. Verifications were performed during the assembly process at either the piece part or sub-assembly level.

As mentioned above, the assessment made in Reference 5 translates the allowable signal degradation per sub-assembly into corresponding molecular fluence levels of contamination per sensitive surface (Tables 1 and 2). By the relation shown in Equation 1, these allowable levels of fluence, Ψ_c (ng/cm^2), that may collect are transformed into corresponding measurable[1] amounts of source flux, Φ_s (ng/cm^{2}hr), that a source may produce.

Directly connecting the amount of collection on a sensitive surface with its source is the geometric transport factor, F_{ij} (Equation 2). These factors have been calculated per sub-assembly from simplified vent path geometries (Reference 6). Table 6 lists the transport factor for each of the most critical paths between source and collector.

The final sub-allocation is that of how much each source may contribute to a collector. A fractional percent, F_s, of the allowable collection is allotted to each source as a weighing factor. This weighing factor is determined by a source's proximity to a collector (geometry), its outgassing characteristics and the susceptibility of the collector.

$$\phi_s\ F_{ij}\ R_q = \psi_c\ F_s\ k \quad (3)$$

At specific collection temperatures there exists particular rates of re-emission[2], k(-20°C) = 7.56 x 10^{-3} hr^{-1} and k(0°C) = 0.0576 hr^{-1}

[1] Flux is measurable via a 15 MHz thermal quartz crystal microbalance (TQCM) at a response rate of R_q = 1.56 ng/cm^{2}Hz.

[2]The values of re-emission are based on constituents found in common spacecraft materials.

(Reference 4). This is important in relating the allowable fluence to the source flux. The validity of the above relation is due to a state of equilibrium between the flux impinging on a collecting surface and the flux re-emitting from the same surface. It is also important to note that this equilibrium condition exists after a period of time much less than the five year EOL.

In order to meet the allowable signal degradation requirements placed on MISR's sensitive surfaces, the contributing source components were required, at a pressure less than 10^{-5} torr, to outgas less than or equal to the source outgassing rates[1] listed in Tables 4 and 5 at the prescribed source and collector temperatures. Each source component or sub-assembly is listed along with the sensitive surface collector responsible for that source level of outgassing. The percent sub-allocated from each collector to a source is listed as well.

In Tables 1 and 2 the lens assembly is listed as a sensitive surface. Although this is the case, it is less susceptible than other sensitive surfaces in the vicinity. In fact, the lens assembly is more critical as a source to the CCD window and therefore must meet a stricter requirement than that placed upon it in Table 2. All other sensitive surfaces remain driving collectors through out the analysis.

As part of the verification procedure the source was tested at a temperature ten degrees warmer than its operating temperature. Also, the TQCM collecting the contaminants was ten degrees colder than the operating temperature of the sensitive surface driving the requirement. All collection requirements were set corresponding to a TQCM's response in Hz/hr.

One scenario from total allocation to TQCM frequency requirement is as follows: The optical through-put is allowed to degrade no more than 5% through EOL (Table 1). From this, the signal degradation at the CCD window shall be no greater than 2.7% (Table 2), 1.8% of which may degrade due to internal MISR sources. This percentage is equivalent to a collectable molecular fluence of 630 ng/cm^2 (Table 3). Sixty percent of this, or 380 ng/cm^2 is sub-allocated to collect from sources in the volume surrounding the CCD (Table 4). With the CCD window collecting at -20°C the flux rate of re-emission is 2.86 ng/cm^{2}hr. A transport factor of 0.0277 from this volume to the CCD window (Table 6) translates the allowable flux to a source flux of 103 ng/cm^{2}hr, or a TQCM collection rate of 65 Hz/hr (1 Hz = 1.56 ng/cm^2) as collected on a -20°C crystal with the source at +20°C (Table 4).

CONTROL PROCEDURES

The preceding methods were undertaken in order to reduce the threat of self contamination. The problem of on-ground environmental contamination was dealt with by monitoring, bagging, purging, and surface cleaning techniques. Internal instrument exposure was limited to environments cleaner than Class 10,000. Prior to assembly optical piece parts were precision cleaned to a particle level (PCL) 150 (Reference 7; MIL-STD-1246), other critical hardware was cleaned to PCL 300 and allowed to degrade to PCL 400 through assembly and test. The non-volatile residue (NVR) levels were not to exceed 1 μg/cm^2 (Level A; MIL-STD-1246).

Monitoring of the contamination fallout (particulate fallout and NVR accumulation) in the vicinity of critical surfaces on the instrument subassemblies was a crucial part of insuring that the instrument met mission requirements. Surface monitoring also included NVR sample wipes and particle tape lifts on the actual instrument surfaces. Documentation of monitoring data and the recleaning performed was done to insure instrument cleanliness. The witness plates were checked twice a week and replaced every two to three weeks.

The cleanliness monitoring equipment included TQCMs to measure in-situ molecular contamination collection in the vacuum chamber environment (controlled to a temperature 10°C colder than the minimum on-orbit operating temperature), anodized aluminum witness plates to measure particle fallout and polished stainless steel witness plates to measure surface NVR levels throughout all assembly and test procedures at the instrument level. Witness samples accompanied the external radiators from painting through pre-launch activities. This provides an estimate of the cleanliness level at launch for the radiating surfaces, which were difficult to visually inspect and to clean.

Data from the monitors was taken and kept in a log with reasonable scrutiny occurring at each entry. This data included; the automated environmental humidity and temperature readings; the results of any flush cleaning that occurred; the results of all particle count and HC levels in residue (quantity and species); the results of analyses performed on witness plates; all sensor locations; all anomalous events; all PFRs; all data showing that surface cleanliness requirements were met for: hardware, ground support equipment, shipping containers, and packaging materials; and thermal-vacuum test contamination data: TQCM (hourly readings), chamber particle fallout, and cold plate analysis. Current totals of particulate and molecular contamination accretion was kept for external surfaces. When a surface was cleaned, the new surface contaminant level was determined and recorded.

During the MISR system thermal vacuum test a "cross-contamination" test per the EOS PAR (Reference 8) was performed. The collection flux requirement of 100 ng/cm^2 hr was met with an actual collection flux of 13 ng/cm^{2}hr (Reference 9). The TQCMs monitoring the collection at the aperture (with the cover opened and closed) showed a remaining fluence of 80 ng/cm^2 at the end of the T/V. The exposed particle witness plates showed a cleanliness level of PCL 200 while the exposed LVR plates showed a maximum collection of 320 ng/cm^2 hydrocarbon/silicone mixture. Since instrument delivery to the spacecraft integration contractor and after system T/V testing the exterior instrument surfaces were tested with results of PCL 300 and NVR Level 200 ng/cm^2.

CONCLUSIONS

Along with the specifics of the analysis, the frame work structure of the assessment is also illustrated. Starting with the performance requirements this frame work sub-allocates these requirements to areas or surfaces of concern and then converts them into equivalent amounts of contamination.

The most sensitive surfaces to contamination are those which are most effected by the collection of small amounts of molecular and particulate contamination. Using the above frame work the most sensitive surfaces to contamination were found to be: the CCD windows, the de-polarizers, the lens assemblies, the calibration plates, the calibration diodes and the thermal radiator surfaces.

The most critical source locations from which these sensitive surfaces may be contaminated, due to the transport factors connecting them, were also defined by this frame work. These included: the volumes surrounding the CCDs, between the CCD windows and the last lens elements, the electronics packaging connecting directly behind the CCD heads, the lens assemblies, the environment outside of the camera housings but inside the MISR assembly, the external environment directly in front of the MISR aperture, and the contamination from the EOS platform and other EOS instruments.

All piece parts were baked out and verified to meet the established requirements prior to assembly. The instrument met the EOS platform cross contamination requirement and all external surfaces were maintained at or below the stated requirements through-out S/C I/T.

ACKNOWLOGEMENTS

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REFERENCES

1) Diner, D.; EOS MISR Instrument Science Requirements; JPL Internal Document D-9090; March 27, 1992.

2) Aveni, G.; MISR Contamination Requirements; JPL Internal Document MISR DFM 421; May 19, 1994.

3) Adapted from: Muscari, J.A.; Non-Metallic Materials Contamination Studies Final Technical Report, Contract 955426 JPL; Martin Marietta Co., Denver Aerospace, MCR-80-637; December 16, 1980.

4) Barengoltz, J.; Report on the Analysis of Contamination Data from WF/PC TV-6 Test; JPL IOM No. 354:JB:88:0329; October 20, 1988.

5) Aveni, G.; MISR Preliminary Contamination Assessment; JPL Internal Document MISR DFM 221; April 30, 1993.

6) Loeb, L.B.; The Kinetic Theory of Gases; Dover Pub. Inc. 3rd ed.; 1961.
7) MIL-STD-1246; Military Standard Product Cleanliness Levels and Contamination Control Program; April 11, 1994.
8) GSFC 420-05-01; Earth Observing System (EOS) Performance Assurance Requirements (PAR) for EOS General Instruments; August 2, 1991.
9) Aveni, G.; Contamination Results from MISR T/V II; JPL Internal Document MISR DFM 1048; May 22, 1997.

TABLE 1.
PERCENT DEGRADATION ALLOCATION PER MISR SUB-SYSTEM.

SUB-SYSTEM WITH CONTAMINATION CONCERN	PERCENT DEGRADATION ALLOCATION	ESTIMATED CONTAMINATION FLUENCE (ng/cm²)
OPTICAL THROUGHPUT	5%	1770
CALIBRATION PLATES	5%	1770
CALIBRATION DIODES	5%	1770
THERMAL RADIATORS	$\Delta\alpha$=0.1	2.0×10^4

TABLE 2.
PERCENT DEGRADATION SUB-ALLOCATION OF OPTICAL THROUGHPUT.

SUB-SYSTEMS OF CONCERN	PERCENT DEGRADATION ALLOCATION	ESTIMATED CONTAMINATION FLUENCE (ng/cm²)
CCDs	2.7%	950
FRONT DE-POLARIZER	1.7%	600
LENS ASSEMBLY	0.6%	220
TOTAL	5.0%	1770

TABLE 3.
PERCENT DEGRADATION SUB-ALLOCATION OF CCDs DUE TO SOURCES.

CONTAMINATION SOURCES	PERCENT DEGRADATION SUB-ALLOCATION	ESTIMATED CONTAMINATION FLUENCE (ng/cm²)
MOLECULAR INTERNAL TO CAMERAS	1.8%	630
MOLECULAR EXTERNAL TO CAMERAS BUT INTERNAL TO MISR	0.4%	140
MOLECULAR EXTERNAL TO MISR	0.2%	70
PARTICULATE	0.3%	110 OR=0.003
TOTAL	2.7%	950

Table 4.
Bakeout Verification Requirements for Internal MISR Sources

Internal MISR Sources	Collector Driving Requirement	Percent of Collector's Allocation (%)[3]	Source Temperature (°C)[4]	Collection Temperature (°C)[5]	QCM Frequency Requirement (Hz/hr)
Vol Surrounding CCD[6]	CCD	60	+20	-20	65
Camera Head Elec Assy[7]	CCD	15	+20	-20	105
Volume Behind CCD[8]	CCD	25	+20	-20	75
Lens Barrel Assembly[9]	CCD	70	+20	-20	50
PIN Diode Light Tube	PIN Diode	100	+15	-10	90
HQE Diode Light Tube	HQE Diode	100	+15	-10	30

Table 5.
Bakeout Verification Limits for External MISR Sources

External MISR Sources	Collector Driving Requirement	Percent of Collector's Allocation (%)	Source Temperature (°C)	Collection Temperature (°C)	QCM Frequency Requirement (Hz/hr)
Calibration Plate Assy	Depolarizer	35	+15	-10	40
Radiators	Cal Plate	10	+35	-10	40
Vol Surnd by Blanket[10]	CCD	100	+15	-20	200
Glint Baffle	Cal Plate	5	+60	-10	45
Cover Assembly	Depolarizer	35	+15	-10	30
Optical Bench[11]	Cal Plate	80	+15	-10	20
Cover MDDA	Depolarizer	5	+40	-10	130
Goniometer Pivot[12]	Cal Plate	5	+15	-10	60

[3]The fractional percent sub-allocated to a source from the collector's allocation (Table 1.).

[4]The verification source temperature is 10 degrees warmer than the sources maximum operating temperature.

[5]The verification collection (QCM) temperature is 10 degrees cooler than the collector's minimum operating temperature.

[6]The volume surrounding the CCD includes the assembled lens barrel assembly, the adjustment rings, and the wire loom.

[7]Verification shall be met after the CCD package is assembled with the electronics board.

[8]The volume behind the CCD includes the assembled camera head housing, the assembled thermal expansion cylinders, and the TEC sub-assembly.

[9]Allocation is in relation to other sources in the volume surrounding the CCD.

[10]Verification shall include the optical bench blanket and all sub-assemblies located beneath it.

[11]Verification shall include stray light baffle.

[12]Verification shall include lubricated bearing.

Table 6.
Transport Factor From Source To Collector

MISR Source	Sensitive Surface (Collector)	Transport Factor F_{ij}
Volume Surrounding CCD	CCD Window	0.0277
Camera Head Electronics Assembly	CCD Window	0.0042
Volume Behind CCD	CCD Window	0.0098
Lens Barrel Assembly	CCD Window	9.1×10^{-7}
Volume Surrounded by Optical Bench Blanket	CCD Window	0.0034
PIN Diode Light Tube	PIN Diode Window	0.0720
HQE Diode Light Tube	HQE Diode Window	0.2150
Calibration Plate Assembly	Front Depolarizer Face	0.0117
Cover Assembly	Front Depolarizer Face	0.0171
Cover MDDA	Front Depolarizer Face	4.75×10^{-4}
Radiators	Calibration Plate	0.0315
Glint Baffle	Calibration Plate	0.0146
Optical Bench	Calibration Plate	0.5786
Goniometer Pivot	Calibration Plate	0.0112